DOI 10.1590/s1982-21702019000200007

ARTICLE

GENERATION AND PERFORMANCE ANALYSIS OF GPS AND GLONASS VIRTUAL DATA FOR POSITIONING UNDER DIFFERENT IONOSPHERIC CONDITIONS

Gabriel Oliveira Jerez[1] - ORCID: 0000-0001-6893-2144

Daniele Barroca Marra Alves[2] - ORCID: 0000-0002-9033-8499

[1] Universidade Estadual Paulista, Faculdade de Ciências e Tecnologia, Programa de Pós-Graduação em Ciências Cartográficas, Presidente Prudente, São Paulo, Brasil.
E-mail: gabriel.jerez@unesp.br

[2] Universidade Estadual Paulista, Faculdade de Ciências e Tecnologia, Departamento de Cartografia, Presidente Prudente, São Paulo, Brasil.
E-mail: daniele.barroca@unesp.br

Received in 3rd November 2018

Accepted in 15th March 2019

Abstract:

Several approaches concerning the use in positioning of GNSS (Global Navigation Satellite Systems) can be considered: systems, applied methods and errors that can affect the signals. Following *the* GLONASS (GLObal NAvigation Satellite System) constellation reestablishment (2011), there was renewed interest in its use with GPS (Global Positioning System). Different possibilities are available concerning applied methods, such as the virtual reference station (VRS) concept (it is possible to obtain data for a virtual station that does not physically exist, using data from a network). One of the main sources of error related to the GNSS signal, is the ionosphere. Many studies have been developed aiming to evaluate GPS positioning quality and influences that can affect it, but there are still several investigation possibilities concerning GLONASS. In this context, this research is intended to assess the GPS/GLONASS virtual data positioning performance considering regions and periods with different ionospheric behavior. A high correlation between the results from virtual and real data (Pearson's correlation coefficients around 0.8) was noticed. GPS/GLONASS data performance presented better mean squared error results compared to GPS alone (average 3D improvement was 45 cm - 49%). In addition, it was possible to verify ionosphere influence in the positioning error, taking into account station region and period of the year.

Keywords: GNSS; GPS/GLONASS; VRS; Ionosphere

How to cite this article: JEREZ, G. O. and ALVES, D. B. M. Generation and Performance Analysis of GPS and Glonass Virtual Data for Positioning UNDER Different Ionospheric Conditions. *Bulletin of Geodetic Sciences*, 25(2): e2019007, 2019.

1. Introduction

GNSS (Global Navigation Satellite Systems) led to fast technological improvement in positioning activities. Nowadays (2019), GLONASS (GLObal NAvigation Satellite System) and GPS (Global Positioning System) are the systems available with full constellations. Since the modernization and reestablishment of GLONASS, interest in the combined use of GPS/GLONASS has been renewed. The use of more than one constellation is important due to the number of visible satellites, which increases the number of available observables and can improve the geometry of satellites (Hofmann-Wellenhof, Lichtenegger and Wasle 2008).

Several factors must be considered to assess positioning quality, for instance the applied positioning methods and the errors that can affect the transmitted signals. Concerning errors, the ionosphere is one of the main sources, mainly for single frequency users. Ionospheric irregularities are related, for instance, to ionospheric scintillation, which can lead to loss of lock and degrade positioning accuracy. Ionospheric influence intensity varies due to the region of station, magnetic activity, solar activity and other factors (McNamara 1991).

Concerning the positioning methods available, in the last decade, Real Time Kinematic (RTK) methodologies have emerged. Use of RTK presents limitations related to baseline length due to space error decorrelation, such as those related to atmospheric effects. In order to overcome this limitation, the concept of positioning based on reference station network emerged. This enabled the development of new methodologies, such as the Virtual Reference Station (VRS) concept (Wu, Kubo and Yasuda 2003). For this method, real data from a GNSS station network are used to generate virtual data, simulating a station near the user (Hofmann-Wellenhof, Lichtenegger and Wasle 2008). In relation to this, a system applying the VRS concept for obtaining GPS virtual data with several options of correction models was developed at UNESP (Alves 2008).

In recent years, several methods were developed aiming to verify the quality of data from the VRS concept. Some positioning methods were applied in this context, considering relative positioning (Alves, Monico and Dalbelo 2007; Alves and Monico 2010; 2011; Alves, Abreu and Souza 2013), RTK (Silva, Monico and Alves 2016; Berber and Arslan 2015) and precise point positioning (Alves, Monico and Dalbelo 2009; Alves and Monico 2011; Alves et al. 2016; Oliveira, Alves and Ferreira 2014a). In addition, some studies investigated the use of some atmospheric models, as in Alves, Monico and Dalbelo (2007), Alves et al. (2016) and Oliveira, Alves and Ferreira (2014a; 2014b). However, in those papers, the VRS use was assessed for GPS data only. With GLONASS modernization, new approaches are required aiming to verify the quality of virtual data and the various application possibilities of the system. In this context, Jerez (2017) performed some improvements in the system developed by Alves (2008), aiming to generate GLONASS and GPS/GLONASS data for virtual stations, enabling new investigation approaches.

In this paper, we present some results from the improved VRS-UNESP version, which enables GLONASS virtual data generation. Virtual data were obtained in RBMC (Brazilian Network for Continuous Monitoring) station positions aiming to evaluate data quality. It therefore became possible to assess real and virtual data performance in precise point positioning. An experiment using GPS and GPS/GLONASS data was performed, considering three Brazilian regions and two periods of the year with different ionospheric activity behavior.

2. Background

In the analysis carried out in this paper, three different approaches were considered: the systems (GPS and GPS/GLONASS data were used); the ionospheric activity (seasonal and regional variations were considered); and the type of data (real and virtual data were assessed). In this section, we present an overview of the main topics considered for analysis in each approach.

2.1 Global Navigation Satellite Systems

GNSS is composed of operational systems, GPS and GLONASS, under development systems, Galileo and BeiDou, and augmentation systems based on terrestrial stations (GBAS - Ground-Based Augmentation System) and satellites (SBAS - Satellite-Based Augmentation System). The main systems, GPS and GLONASS, started to be developed in the seventies and, nowadays, are the systems with full global coverage.

GPS is the United States' contribution to GNSS. The constellation consists of a minimum of 24 operational satellites deployed in six orbital planes. The system reached full constellation in 1995 and, since then has been modernized with new satellites (Hofmann-Wellenhof, Lichtenegger and Wasle 2008; Langley, Teunissen and Montenbruck 2017). The GPS modernizations brought several improvements and the development of new carrier frequencies. Nowadays (2019), GPS III/Block IIIF is under development, where a fourth civil signal will be available (L1C) (GPS 2018).

GLONASS was initially developed by the former Union of Soviet Socialist Republics, and, nowadays, the Russian government is responsible for the system. The constellation has 24 operational satellites, the full constellation was also achieved in 1995 (Hofmann-Wellenhof, Lichtenegger and Wasle 2008; Revnivykh et al. 2017; Langley, Teunissen and Montenbruck 2017). After reaching full constellation, GLONASS passed through a degradation period due to lack of funding between 1996 and 1998 and the short lifetime of the first-generation satellites. In 2000 a restoration and modernization plan was initiated and, since then, new satellite generations have been developed, and the constellation was reestablished in 2011. Additionally, there were improvements in the time and reference systems and an increase in the number of monitoring stations (Hofmann-Wellenhof, Lichtenegger and Wasle 2008; Revnivykh et al. 2017).

Before the GLONASS modernization, variable and unsatisfactory results were obtained with the combined use of GPS and GLONASS systems in investigations such as Bruyninx (2007) and Polezel (2010), due to, among other factors, unevenness in the amount of visible GLONASS satellites available. After GLONASS constellation reestablishment, more recent papers have shown the improvements that can be achieved with the use of GPS/GLONASS combined data, for instance Pan et. al (2014) and Ventorim and Dal Poz (2016).

2.2 Ionospheric effect

GNSS signals can be affected by several errors related to the satellite (orbit, clock, relativistic, hardware delay, antenna phase center, wind-up phase), to the signal propagation (troposphere, ionosphere, multipath, Earth's rotation), to the receiver (clock, channels, antenna phase center, hardware delay, loss of lock, wind-up phase) or to the station (coordinates, multipath, ocean loading, pole tide, atmospheric pressure) (Monico 2008). The atmosphere has a great influence in GNSS signal propagation and the ionosphere is one of the main sources of degradation and error (Seeber 2003).

Ionospheric effects are related to TEC (Total Electron Content), which corresponds to the total number of free electrons in a one squared meter column, from the receiver to the satellite. These values, which vary in time and space, are related to the location on the Earth's surface, geomagnetic activity, solar ionization flow, season and sunspot cycles (McNamara 1991).

Taking the position on the Earth's surface into consideration, electron density is higher in the equatorial region (where the Brazilian territory is located). In mean latitude regions the electron density is less intense and in higher latitudes its behavior is less predictable. In the equatorial region, the ionospheric effect is related, among other factors, to the Equatorial Ionization Anomaly (EIA), with higher intensity in the local anomaly peak (approximate geomagnetic latitude of 20°). The EIA is generated in the magnetic equator, the equatorial ionosphere plasma is lifted in daylight and intensified after sunset (21h LT - Local Time). The plasma diffuses at low latitudes due to pressure gradients and gravity action. This phenomenon is known as the fountain effect (de Rezende et al. 2007; Moraes et al. 2018). That makes the Brazilian region an important location for research related to this issue.

The time variations can be divided into daily, seasonal or long periods. The daily variations occur due to changes in the ionospheric regions caused by the recombination of electrons and ions. The seasonal variations are related to changes in electron density due to variation in the sun zenith angle (also a daily variation) and because of changes in the neutral atmosphere, with more intense activity during summer and lower activity during winter. And the long period cycles correspond to intervals of approximately 11 years, associated with sunspot occurrence (McNamara 1991; Vani, Shimabukuro and Monico 2017).

2.3 Positioning Methods

Real Time Kinematic positioning has been the issue of several recent research papers aiming to improve its use, such as Khodabandeh and Teunissen (2016), Tatarnikov, Stepanenko and Astakhov (2016) and Gao et al. (2018). Besides its benefits, RTK use can encounter limitations related to the baseline, which should not cross 20 km due to the spatial error decorrelation, for instance, those related to atmospheric effects and satellite orbits. The first approaches that aimed to overcome these limitations became possible due to the concept of positioning based on reference station networks (Wu, Kubo and Yasuda 2003). In this scenario, new approaches became possible with new methods applying partial derivatives, conditional adjustment, interpolation and virtual reference station (Alves 2008; Hofmann-Wellenhof, Lichtenegger and Wasle 2008).

The VRS concept consists of generating observation data from a station that does not exist physically near to the user. This concept makes it possible to increase the distance between the receiver and the reference station, compared to standard RTK. In this method, the data collected by the receivers in each reference station are controlled from a central station which performs the processing needed to deliver to the user the information from the virtual station that is required to be used (Alves 2011). For this method, a station network, a central station and a bidirectional link are needed. The user sends his approximate location to the central station which identifies the nearest network station. This station will become the base station (Hofmann-Wellenhof, Lichtenegger and Wasle 2008).

With the VRS concept, the base station cannot be confused with the base station from the relative positioning. In the VRS case, the base station is the station from the network that is closest to the user and will have its data used to obtain data for the virtual station, while in the relative positioning case the base station is the one with known coordinates, that will be used to estimate the user coordinates. Figure 1 shows the VRS concept. As can be seen, using the approximate position sent by the user, the central station identifies the nearest station from the network. Using the real data from the base station, virtual data for the virtual station are calculated. This way, the user can normally collect GNSS data and then, using the virtual station, estimate his position, for instance, performing a relative positioning (Alves 2008).

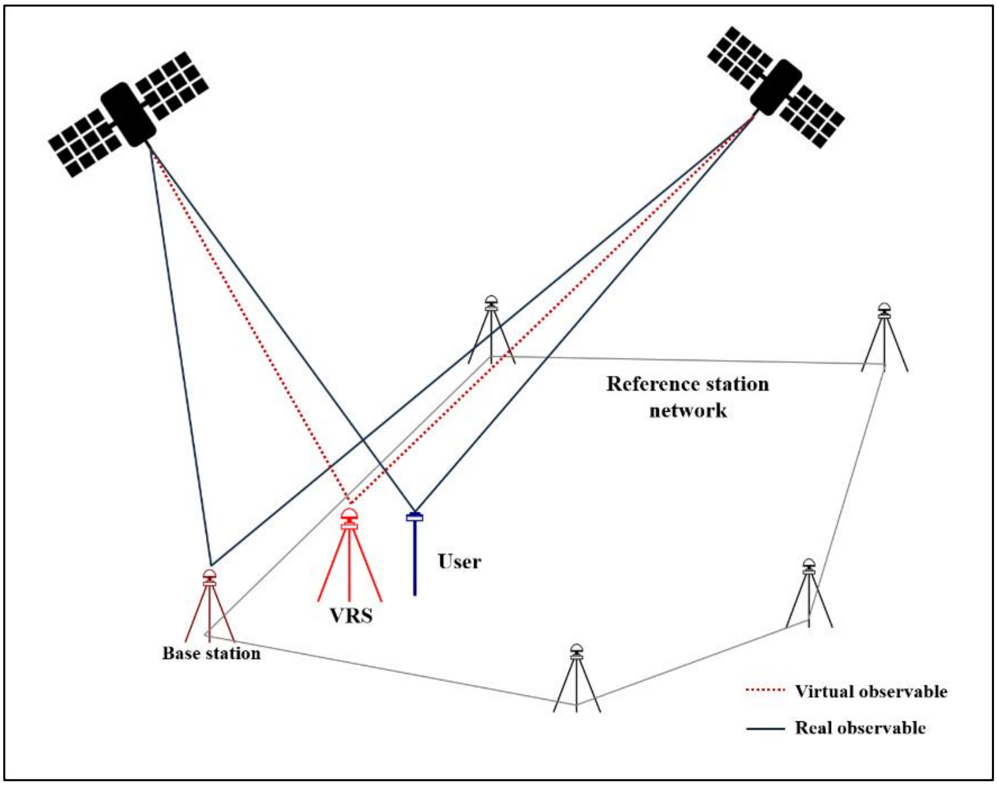

Figure 1: VRS concept representation.

Basically, in order to generate virtual data from real data we have to apply three corrections, geometric displacement, tropospheric and ionospheric correction. In the system developed by Alves (2008), several model corrections were implemented, and several variables considered. Many errors can influence the determination of virtual data, such as orbit error and multipath from the base station. It is possible to model or to ignore them, according to the precision level needed (Hofmann-Wellenhof, Lichtenegger and Wasle 2008). The development of the improved VRS-UNESP version considered the differences between GPS and GLONASS, for instance the CDMA (Code Division Multiple Access) and FDMA (Frequency Division Multiple Access) techniques (Jerez 2017).

3. Methods

In this paper, six GNSS stations from RBMC (Brazilian Network for Continuous Monitoring) were selected, three were used as base stations and the other three had their positions used for the generation of virtual observables. Figure 2 presents the locations of the selected stations, aiming to represent three Brazilian regions with different ionospheric behavior. A region near Geomagnetic Equator (RECF and PBJP), another affected by the Fountain Effect (SPTU and SPDR) and another with lower ionospheric activity (IMBT and SCFL). RECF (Recife), SPTU (Tupã) and IMBT (Imbituba), presented as red squares, were used as base stations. PBJP (João Pessoa), SPDR (Dracena) e SCFL (Florianópolis), presented as green circles, had their positions used for generating virtual data. Table 1 shows the distances between base and virtual stations.

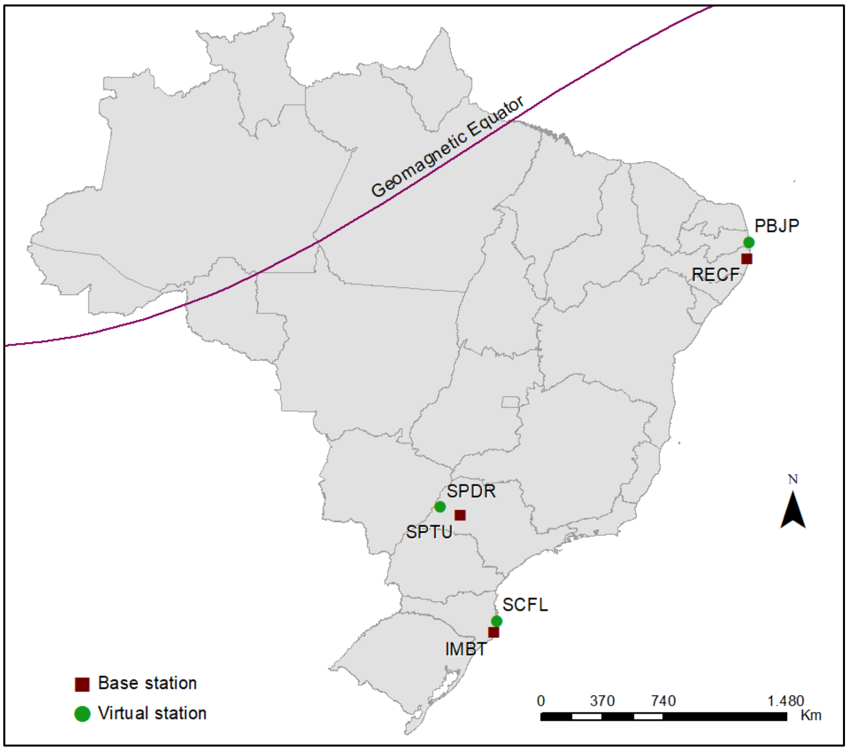

Figure 2: Base and virtual stations locations.

Table 1: Distance between base stations and virtual stations positions.

Base	VRS	Distance (km)
RECF (Recife)	PBJP (João Pessoa)	100
STPU (Tupã)	SPDR (Dracena)	115
IMBT (Imbituba)	SCFL (Florianópolis)	75

In this research, we applied the virtual reference station concept, using the improved version of the VRS-UNESP system. The periods considered were June and October 2014, with 30 minutes of data collection, starting at 00h UT-3 - Universal Time (21h LT). The selection of these months was intended to take into consideration a period with low ionospheric influence and another with high ionospheric activity, June and October, respectively. The last eleven-year solar cycle (cycle 24) also had its peak between 2013 and 2014.

The observations from RBMC stations, PBJP, SPDR and SCFL, and the files generated for their positions were processed using the online software CSRS-PPP (Canadian Spatial Reference System – Precise Point Positioning) from NRCan (Natural Resources Canada) in the static mode. We used dual-frequency data, collected using 10° elevation mask, 15 seconds sample rate, with GPS and GPS/GLONASS data files. The processing results were compared with the official station coordinates, provided by the Brazilian Institute of Geography and Statistics, transformed to the same reference frame and updated to the date of the campaign. The mean squared errors (MSE) were obtained from these discrepancies and the standard deviations. Figure 3 presents the processing configurations, considering that for each position real and virtual data were processed using GPS and GPS/GLONASS data files for June and October.

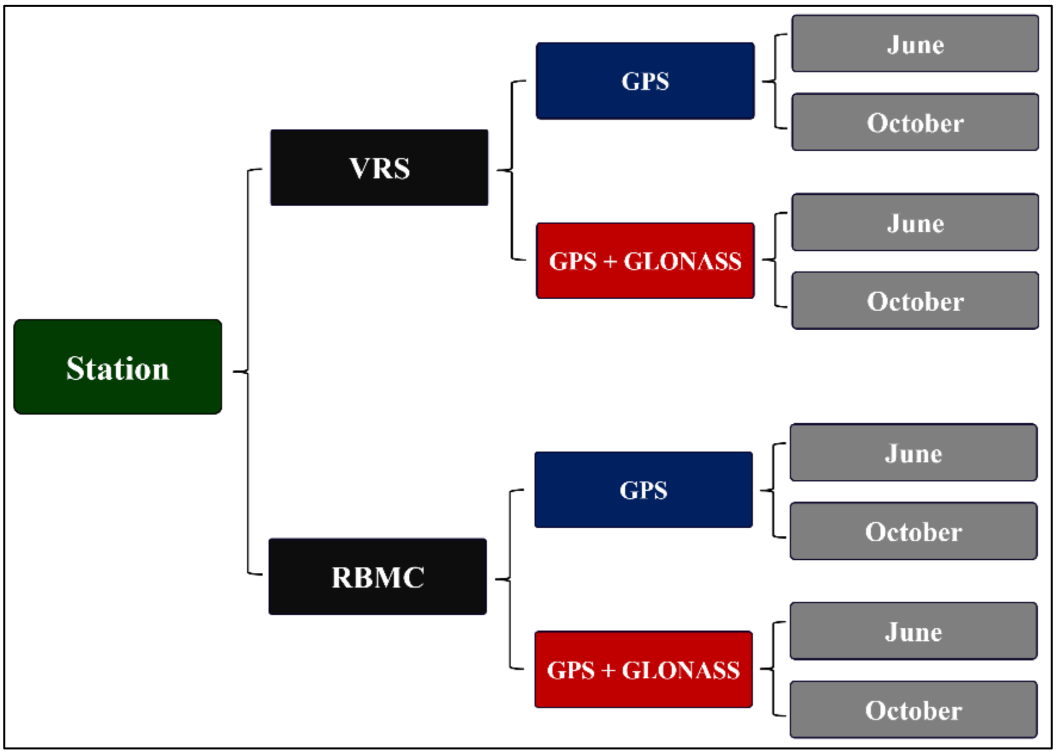

Figure 3: Processing configurations used for each station.

4. Results and Discussions

MSE obtained are presented according to the station used. Figure 4 presents the results of PBJP station (region near the geomagnetic equator) data, Figure 5 presents those from SPDR (region affected by the fountain effect) and Figure 6 presents the results of SCFL (region with lower ionosphere activity). Only days with full datasets were retained in the analysis; days with lack of data were suppressed.

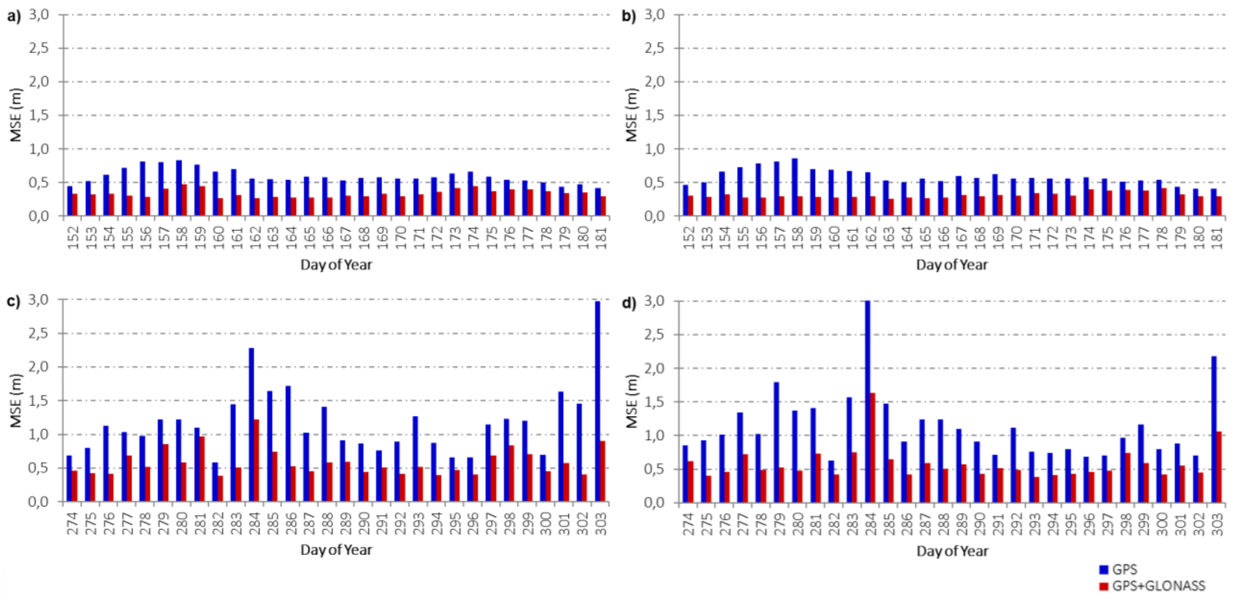

Figure 4: MSE results for PPP processing considering PBJP station. a) Virtual data generated for June; b) Real data collected in June; c) Virtual data generated for October; d) Real data collected in October.

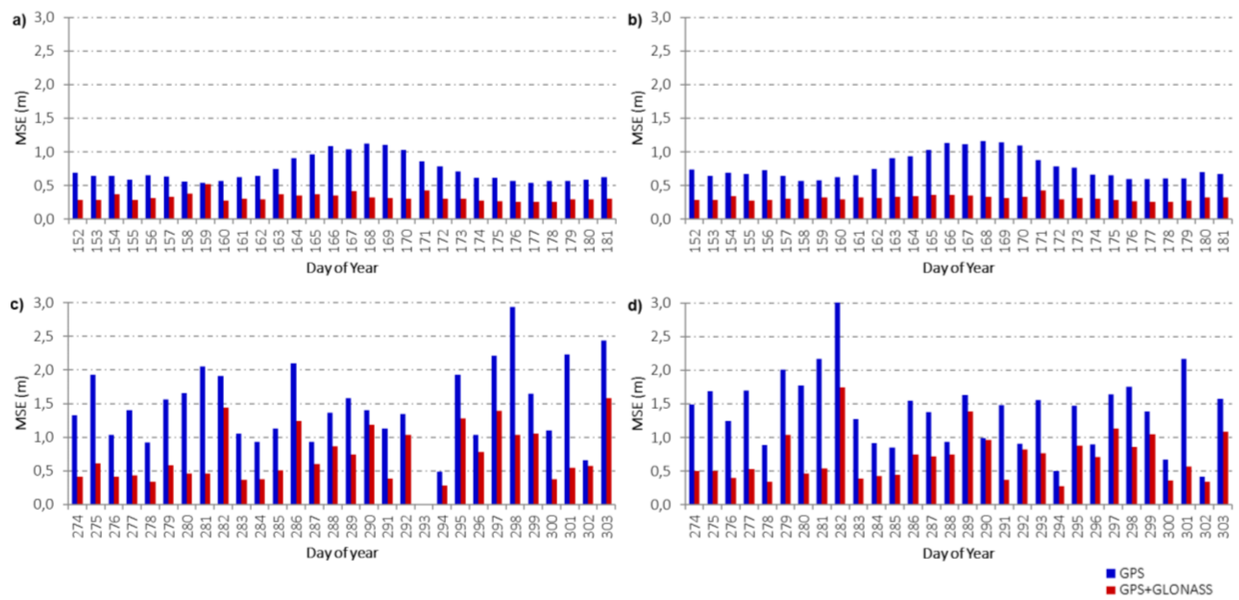

Figure 5: MSE results for PPP processing considering SPDR station. a) Virtual data generated for June; b) Real data collected in June; c) Virtual data generated for October; d) Real data collected in October.

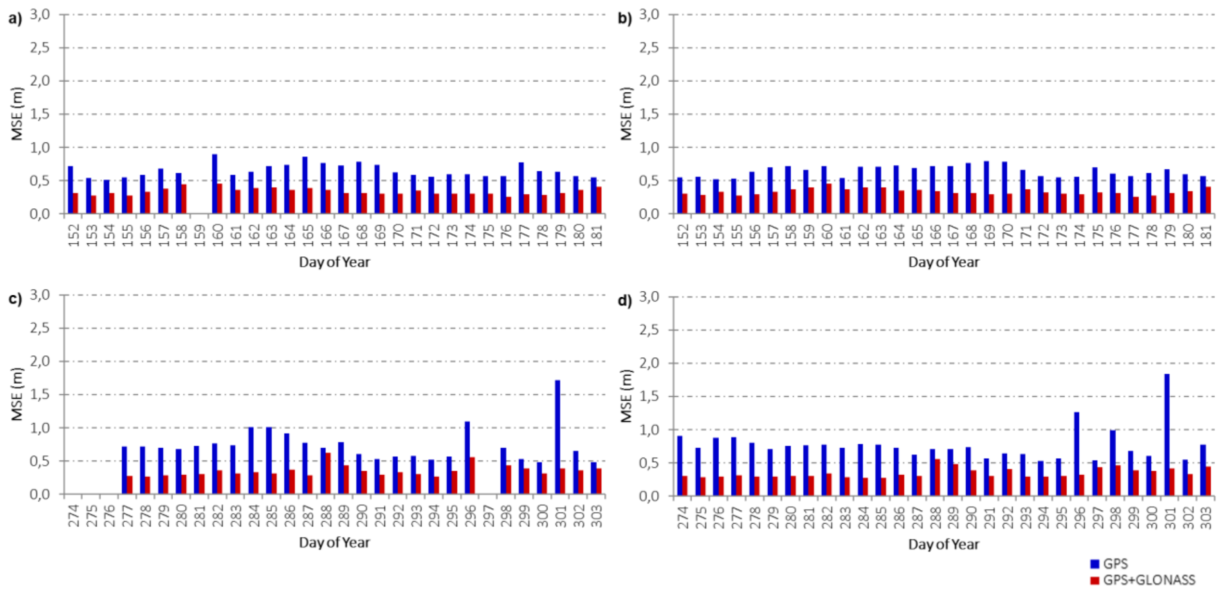

Figure 6: MSE results for PPP processing considering SCFL station. a) Virtual data generated for June; b) Real data collected in June; c) Virtual data generated for October; d) Real data collected in October.

All the days analyzed presented improvement in MSE, with virtual and real data, by using GPS/GLONASS combined data. The similarity in behavior of real and virtual data is evident, particularly for data collected in June. The influence of station position is also clear; the one located in the south (SCFL – Figure 6) produced the better MSE results. On the other hand, the station located in the region most affected by the ionosphere (SPDR – Figure 5) had the most variable results, particularly for data collected in October, the period also characterized by more intense ionospheric activity. Considering the improvement in the MSE by adding GLONASS data, in Table 2 it is possible to verify the increase in the number of visible satellites. Table 2 presents the mean values considering data from June, October and both months. In general, adding GLONASS data resulted in a mean increase of 8 to 9 satellites.

The mean and standard deviations of improvements obtained by using GPS/GLONASS data for each station are summarized in Table 3. It can be seen that the mean and standard deviation values varied from one station to the other, but, considering real and virtual data, the order of error magnitude was very similar.

Table 2: Mean number of GPS and GLONASS satellites visible for each station.

Station	Period considered	VRS		RBMC	
		GPS	GPS+GLONASS	GPS	GPS+GLONASS
PBJP	June	14	22	16	25
	October	10	19	11	20
	General	12	20	13	23
SPDR	June	13	21	14	22
	October	9	18	10	19
	General	11	19	12	21
SCFL	June	12	20	13	21
	October	9	18	9	18
	General	11	19	11	19

Table 3: Means and standard deviations of obtained improvements by using GPS/GLONASS data.

Station	Data	Month	Improvement with GPS+GLONASS	
			Mean (cm)	Standard Deviation (cm)
PBJP	VRS	June	25.6	10.4
		October	59.7	41.1
	RBMC	June	27.6	12.8
		October	56.2	33.0
SPDR	VRS	June	40.4	18.3
		October	76.1	44.4
	RBMC	June	46.5	17.6
		October	70.0	46.2
SCFL	VRS	June	30.4	11.0
		October	38.8	25.0
	RBMC	June	31.3	8.2
		October	42.5	26.2

Figure 7 presents the absolute differences of MSE values for each day, comparing virtual and real data. The greatest differences can be confirmed as happening in October, a period characterized by intense ionosphere activity behavior. For PBJP data (Fig. 8a), the mean differences considering data collected in June was about 3.8 cm and 27.5 cm in October. Considering the whole period, the mean value was 15.6 cm. SPDR station (Fig. 8b) presented values around 6.1 cm and 23.8 cm in June. Considering data collected in October, when all data was considered, the mean value was 14.8 cm. And with SCFL station data (Fig. 8c), the mean differences were about 6.3 cm for data collected in June, and 10.5 cm for data from October. Considering both months the mean value was 8.3 cm. Once again, ionosphere influence in the positioning error considering station, region and period of the year was observed, with lower values for data collected in June and for the region less affected by ionosphere (SCFL station).

Table 4 presents minimum, maximum and mean percentages of improvement by using GPS/GLONASS combined data for real and virtual data, considering each station. The smaller percentage improvement value, after adding GLONASS data, was for SPDR station using real data, with 9% improvement. The biggest occurred at the same station with virtual data (77.79% improvement).

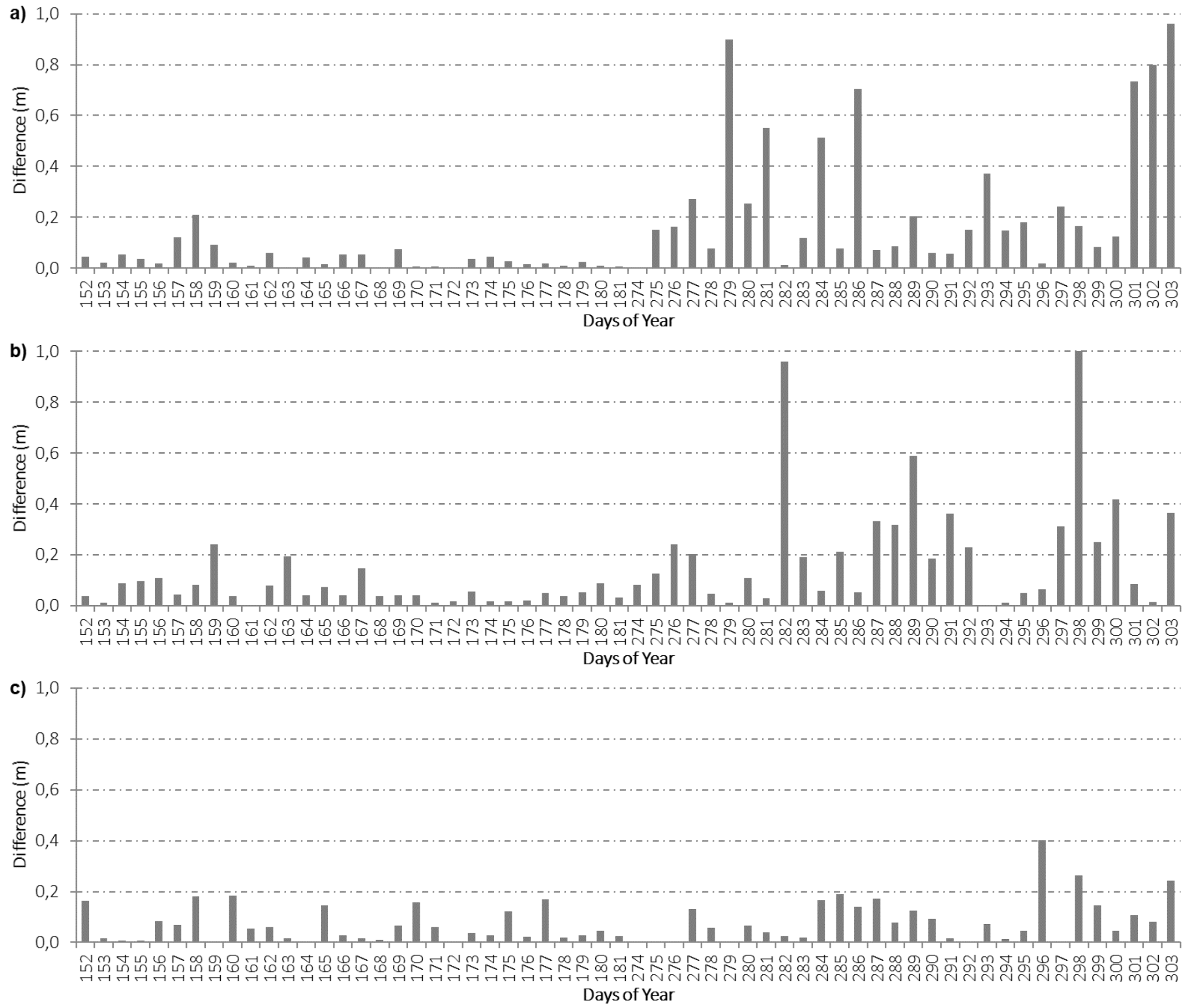

Figure 7: Differences between MSE results obtained from real and virtual data a) PBJP station; b) SPDR station; c) SCFL station.

Table 4: Improvement percentages (minimum, maximum and mean) of GPS/GLONASS combined processing using virtual and real data.

Station	Improvement	VRS (%)	RBMC (%)
PBJP	Minimum	11.95	22.09
	Maximum	72.48	70.93
	Mean	44.42	46.05
SPDR	Minimum	13.05	08.86
	Maximum	77.79	74.98
	Mean	51.66	52.48
SCFL	Minimum	10.64	21.38
	Maximum	77.08	77.59
	Mean	48.18	49.04

Figure 8 shows the percentages of improvement by using GPS/GLONASS real and virtual data for three stations and all days considered. It is possible to see that, besides a bigger variability in results for data collected in October, the behavior of real and virtual data was similar across almost all days considered.

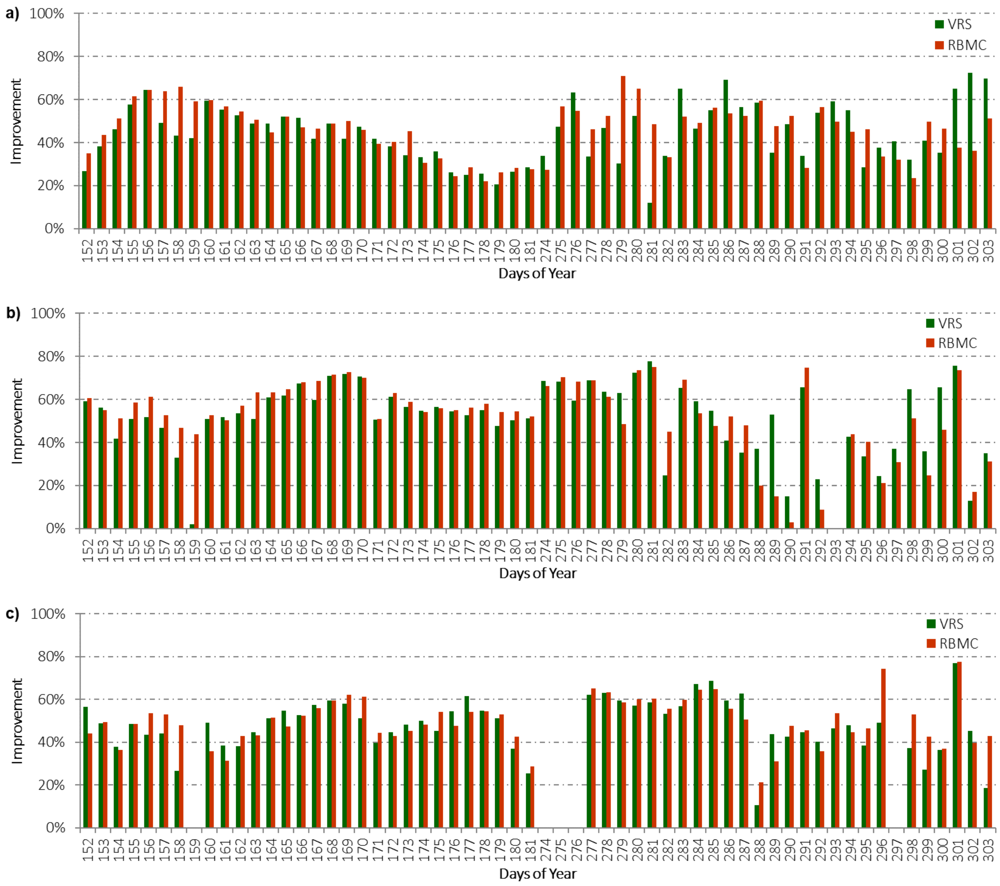

Figure 8: Comparison of MSE improvement percentages by using GPS/GLONASS considering virtual (VRS) and real data (RBMC) a) PBJP station; b) SPDR station; c) SCFL station.

Table 5 presents the Pearson’s correlation coefficients between virtual and real data, considering GPS and GPS/GLONASS data. In a general way, real and virtual data presented high correlation values, with values of about 0.8.

Table 5: Pearson’s correlations for results from GPS and GPS/GLONASS data and virtual and real data.

Station	Constellation/Data	Correlation
PBJP	GPS (real x virtual)	0.821
	GPS/GLONASS (real x virtual)	0.872
	GPS x GPS/GLONASS (virtual)	0.773
	GPS x GPS/GLONASS (real)	0.907
SPDR	GPS (real x virtual)	0.819
	GPS/GLONASS (real x virtual)	0.865
	GPS x GPS/GLONASS (virtual)	0.763
	GPS x GPS/GLONASS (real)	0.728
SCFL	GPS (real x virtual)	0.834
	GPS/GLONASS (real x virtual)	0.773
	GPS x GPS/GLONASS (virtual)	0.281
	GPS x GPS/GLONASS (real)	0.231

In the MSE from the three stations (Fig. 5, 6 and 7), a high similarity can be seen between real and virtual data, not only considering the MSE order of magnitude, but also its behavior, mainly for data collected in June. In June, all the results from GPS/GLONASS data achieved values below 0.5 m, on the other hand, results from GPS only showed more variable results.

In October, SCLA (region with lower ionosphere activity) presented the more regular results, despite some bigger differences on some days. However, even taking these days into consideration, the behavior of real and virtual data was similar. Considering PBJP (region near the geomagnetic equator) and SPDR (region affected by the fountain effect), the greater variability of results from October data was clear, even though PBJP presented more similar MSE values considering results from real and virtual observables.

Apart from the MSE differences noted from one month to the other, the mean percentages of improvement with the GLONASS data added to the GPS was also similar for both months. In June, the mean improvement by using GPS/GLONASS data was 49.0%, and in October, 48.6% considering the three stations and results from real and virtual data. In the same way, considering real and virtual data, the mean percentages of improvement were compatible. For PBJP station the mean improvement by using GPS/GLONASS data was about 45%, for SPDR station, 52% and for SCFL station, about 49%.

Considering the Pearson’s correlation coefficients (Table 5), high values were obtained from real and virtual data (around 0.8). It was also possible to see significant correlations between GPS and GPS/GLONASS results, except for the station located in the region with lower ionospheric activity (SCFL). As the errors present small values in this region, the results are more sensitive to small variations which could explain the decrease in the correlations between the results from some configurations.

Of the papers previously quoted, those that investigated the use of virtual data for PPP in static mode were Alves, Monico and Dalbelo (2009), Alves and Monico (2011), Alves et al. (2016) and Oliveira, Alves and Ferreira (2014a). In these papers, a similar approach was assessed concerning the method (PPP) and the software used (same software in different version) compared to the present work. In those papers atmospheric models were evaluated for generating virtual data. In the best scenarios they achieved mean MSE at decimeter or even centimeter level. The tests that also used data from RBMC stations had important differences compared to this paper, mainly for the constellations considered and the data collection time. The works mentioned used 24 hours data for the analysis, in this paper we used 30 minutes. It is worthwhile to highlight that the main topic of those papers was to evaluate methods for virtual data generation and atmospheric models used. On the other hand, in this work, we intended to assess the quality of virtual GLONASS data, the usability of those combined with GPS, and to evaluate the influence of ionospheric activity in the GNSS positioning.

The use of real stations positions to generate virtual data enabled the assessment of VRS data quality, because of the possibility of comparing the results from processings using real and virtual data. As observed in the previous papers, something that has to be highlighted is the similarity between results from virtual and real data. All processing configurations used for the analysis also presented results with a similar order of magnitude. This was noted not only with the MSE behavior, but also in the mean and standard deviation values, and, furthermore, in the correlation analysis performed.

5. Conclusions

In this paper, we aimed to assess the performance of GPS/GLONASS virtual data for positioning under ionospheric influence. For this purpose, three Brazilian regions and two periods with different ionospheric behavior were selected.

The results have evidenced the ionospheric influence in the positioning, considering the behavior of results and the order of magnitude of errors. The highest and more irregular values were those obtained with October data, and the station with more regular results and smaller errors was the one in the region with lower ionosphere activity (SCFL) in both periods considered.

Considering the use of GPS and GPS/GLONASS data, all configurations presented improvement in positioning with the use of both constellations combined data. The results were variable from one region to the other, but between real and virtual data very similar results were obtained. The mean improvement was about 45 cm for all the processes performed, which corresponds to a 49% mean improvement. Results presented high similarity between real and virtual data, with correlation coefficients around 0.8.

Acknowledgment

The first author acknowledges CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for the master's scholarship.

Author´s Contribution

Both authors conceived the ideas; Jerez, G. O. developed the improvements in the VRS-UNESP, software developed by Alves, D. B. M. Jerez, G. O. performed the experiments and wrote the manuscript; Both authors contributed to the analysis and discussions of the results and participated in the editing of the paper.

REFERENCES

Alves, D. B. M. Monico, J. F. G. and Dalbelo, L. F. A. 2007. Geração de VRS a partir de Modelos Atmosféricos: Conceito, Implementação e Resultados. Boletim de Ciências Geodésicas, 13(2), pp.316-336.

Alves, D. B. M. 2008. Posicionamento Baseado em redes GPS utilizando o conceito de estação virtual. PhD. Universidade Estadual Paulista.

Alves, D. B. M. Monico, J. F. G. and Dalbelo, L. F. A. 2009. Análise do modelo troposférico empregado na geração de uma estação de referência virtual utilizando o posicionamento por ponto preciso. Boletim de Ciências Geodésicas, 15(3), pp.39-53.

Alves, D. B. M. and Monico, J. F. G. 2010. Geração de dados GPS de pseudodistância para uma estação virtual: métodos, implementação e análise dos resultados. Pesquisas em Geociências, 37(1), pp.3-12.

Alves, D. B. M. and Monico, J. F. G. 2011. GPS/VRS positioning using atmospheric modeling. GPS Solutions, 15(1), pp.253-261.

Alves, D. B. M. Abreu, P. A. G. and Souza, J. S. 2013. GNSS: status, modelagem atmosférica e métodos de posicionamento. Revista Brasileira de Geomática, 1(1); pp.2-7.

Alves, D. B. M. Sapucci, L. F. Marques, H. A. de Souza, E. M. Gouveia, T. A. F. and Magário, J. A. 2016. Using a regional numerical weather prediction model for GNSS positioning over Brazil. GPS Solutions, 20(4), pp.677-685.

Berber, M. and Arslan, N. 2015. Atmospheric Effects on RTK Network in Florida. Boletim de Ciências Geodésicas, 21(4), pp.814-831.

Bruyninx, C. 2007. Comparing GPS-only with GPS + GLONASS positioning in a regional permanent GNSS network. GPS Solutions, 11, pp.97-106.

de Rezende, L. F. C, de Paula, E. R., Kantor, I. J., Kintner, P. M. 2007. Mapping and survey of plasma bubbles over Brazilian territory. The Journal of Navigation, 60, pp. 69-81.

Gao, W. Meng, X Gao, C Pan, S. and Wang, D. 2018. Combined GPS and BDS for single-frequency continuous RTK positioning through real-time estimation of differential inter-system biases. GPS Solutions, 22 (1), pp.20-33.

GPS World, 2017. Directions 2018: GLONASS focuses on user needs. [online] (updated December 2017). Available at: <http://gpsworld.com/direction-2018-glonass-focuses-on-user-needs/> [Accessed 13 December 2017].

GPS, 2018. Current and Future Satellite Generations. [online] (updated September 2018). Available at: <http://www.gps.gov/systems/gps/space> [Accessed 10 October 2018].

Hofmann-Wellenhof, B. Lichtenegger, H. Wasle, E. 2008. GNSS – Global Navigation Satellite Systems GPS, GLONASS, Galileo, and more. New York: Springer-Verlag.

Jerez, G. O. 2017. Análise da integração GPS/GLONASS para posicionamento sob efeito de cintilação ionosférica. Master. Universidade Estadual Paulista.

Khodabandeh, A. and Teunissen, P. J. G. 2016. PPP-RTK and inter-system biases: the ISB look-up table as a means to support multi-system PPP-RTK. Journal of Geodesy, 90, pp.837-851.

Langley, R. B., Teunissen, P. J. G., Montenbruck, O. 2017. Introduction to GNSS. In: Teunissen, P., Montenbruck, O., eds. 2017. Springer Handbook of Global Navigation Satellite Systems. Springer: Cham, pp. 3-23.

McNamara, L. F. 1991. The ionosphere: communications, surveillance, and direction finding. Florida: Krieger Publishing Company.

Monico, J. F. G. 2008. Posicionamento pelo GNSS: Fundamentos, Definição e Aplicação. São Paulo: Editora UNESP.

Moraes, A. O., Vani, B. C., Costa, E., Abdu, M. A, de Paula, E. R., Santos, J. S., Monico, J. F. G., Forte, B., Negreti, P. M. S., Shimabukuro, M. H. 2018. GPS Availability and Positioning issues when the signal paths are aligned with ionospheric bubbles. GPS Solutions, 22(4), pp. 95-106.

Oliveira, A. D. F. D. Alves, D. B. M. and Ferreira, L. D. D. 2014a. Análise de Modelos Troposféricos no posicionamento baseado em redes usando o conceito de VRS. Boletim de Ciências Geodésicas, 20(1), pp. 39-53.

Oliveira, A. D. F. Alves, D. B. M. and Ferreira, L. D. D. 2014b. Avaliação de diferentes modelos troposféricos de previsão numérica de tempo no posicionamento em redes. Revista Brasileira de Cartografia, 1(66/3), pp. 691-704.

Pan, L. Cai, C. Santerre, R. and Zhu, J. 2014. Combined GPS/GLONASS precise point positioning with GPS ambiguities. Sensors, 14 (9), pp.17530-17547.

Polezel, W. G. C. Investigações sobre o impacto da modernização do GNSS no posicionamento. 2010. Master. Universidade Estadual Paulista.

Revnivykh, S. Bolkunov, A. Serdyukov, A. and Montenbruck, O. 2017. GLONASS. In: Teunissen, P., Montenbruck, O. (Eds). Springer Handbook of Global Navigation Satellite Systems. Springer, Cham, pp. 219-245.

Seeber, G. 2003. Satellite Geodesy: Foundations, Methods, and Applications. Berlin, New York: Walter de Gruyter.

Silva, H. R. Monico, J. F. G. and Alves, D. B. M. 2016. Análise do desempenho do RTK em rede no Brasil sob efeito da cintilação ionosférica. Revista Brasileira de Cartografia, 68(10), pp.2083-2102.

Tatarnikov, D. V. Stepanenko, A. P. and Astakhov, A. V. 2016. Moderately compact helix antennas with cutoff patterns for millimeter RTK positioning. GPS Solutions, 20, pp.587-594.

Vani, B. C. Shimabukuro, M. H. Monico, J. F. G. 2017. Visual exploration and analysis of ionospheric scintillation monitoring data: The ISMR Query Tool. Computers & Geosciences, 104, pp.125-134.

Ventorim, B. G. and Dal Poz, W. R. 2016. Avaliação do desempenho dos sistemas GPS e GLONASS no posicionamento por ponto preciso, combinados e individualmente. Boletim de Ciências Geodésicas, 22(2), pp.264-281.

Wu, F. Kubo, N. and Yasuda, A. 2003. Estimation of Atmospheric Delays Using Multiple Reference Stations for RTK-GPS Positioning. In: ION GPS. Portland, Oregon: United States.